PARALLEL, STAGED OPENING SWITCH POWER CONDITIONING TECHNIQUES
FOR FLUX COMPRESSION GENERATOR APPLICATIONS

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Introduction

Pulse power systems which are capable of delivering several megajoules of electrical energy to experimental loads in a fraction of a microsecond are currently of interest in the scientific community for driving a variety of plasma and particle beam loads. Practical considerations of cost and complexity frequently demand that system designers make use of primary power sources that are both compact and economical. Such compact power sources as flux compression generators and large relatively low voltage capacitor banks represent economical ways to make multi-megajoule level energies readily available. Unfortunately, large banks and generators invariable suffer because their characteristic energy delivery times are much longer than the time scales that are required for many experiments. Thus intermediate power compression systems are usually a part of the conceptual package, and conditioning techniques based upon inductive (magnetic) energy storage represent economical, compact approaches which complement the size and cost characteristics of these primary power sources.

The challenge associated with the use of the inductive power conditioning systems is, of course, the opening switch needed to release energy from the store, and the fundamentally long time scales of these primary energy sources further complicate an already difficult switching task. At present two opening switch techniques which have been successfully demonstrated at the megampere level are: the electrically exploded fuse, and the mechanically or explosively ruptured conductor switch. While fuse systems have successfully conducted currents of several tens of megamps, and have interrupted these currents in about 200 nS while withstanding several hundred kilovolts (1), simple circuit calculations show that fuses designed for sub-microsecond interrupt times, exhibit very large losses when required to conduct for 10's of microseconds. And fuses properly sized for long conduction time demonstrate unacceptably long interruption times. On the other hand, ruptured conductor switches ("breakers") which can be sized to retain cold metal conductivity (and the associated low losses) in the presence of megamp current for long periods cannot, in general, be opened in submicrosecond times.

A comparison of the performance of these two types of opening switches for long time scale systems is shown in the circuit calculations presented in Figure 1. For this calculation, a simplified circuit consisting of a 10 MJ capacitor bank operating at 60 KV with a 35 microsecond quarter period is switched into a 20 nH load. These bank parameters are characteristic of such systems as the Shiva Star system if it were connected for "all parallel" operation, and the load inductance is characteristic of a variety of plasma or plasma-switch experiments currently under consideration in the community.(2,3) Two models of opening switches are employed: the "fuse" is described by an emperical model which gives material resistivity as a function of specific internal energy (where internal energy is the result of ohmic heating in the fuse). Resistivity determined by the model is then used to evaluate fuse resistance from the known fuse geometry. The "breaker" is described as a fuse of varying cross-section. The same resistivity model is employed but, in addition, the cross-section of the conductor is reduced by an externally imposed function which approximately describes the burn of a small high explosive (HE) charge transverse to the direction of current flow. The current traces in the figure show a 2-3 microsecond risetime for the current in the load in the case of the breaker and a more than 5 microsecond risetime for the fuse. In order to attain this relatively slow risetime with the fuse it has been necessary to size the fuse so that it interrupts about 25% before the full quarter period of the bank. And hence the fuse delivers considerably less current to the load compared to that delivered by the breaker. And even with a somewhat optimistic model, the breaker displays risetimes in the load which are still long compared to the 100-200 nS rise times required for many loads of current interest.
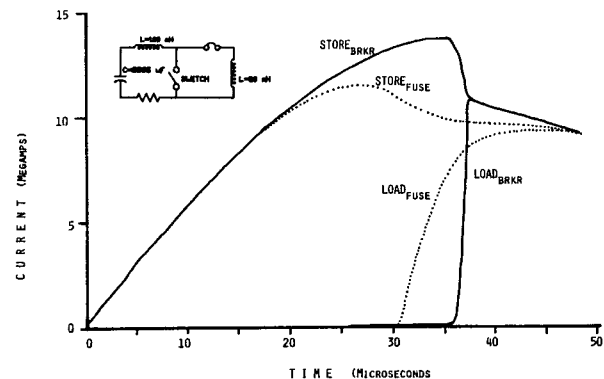
Figure 1   Circuit Model Calculations

An obvious approach to this dilemma is, then, to combine the two elements in a "staged" switching system in which the ruptured conductor switch carries the current in the inductor for the relatively long period of time needed to "charge" the inductor from a slow source. This "breaker" then opens in times of a few microseconds, transfers current to another switch element which may be a high current, high speed fuse. The fuse accepts the current during the microsecond long times required for the breaker to open, and to establish itself as a high resistance path capable of supporting relatively high voltages. The fuse then opens in times characteristic of the fast interruption already demonstrated in previous work (4).

The Air Force Weapons Laboratory, working jointly with Los Alamos National Laboratory, has conducted a series of experiments directed at exploring staged switching techniques for use in opening switch applications which require the conduction of very high currents (or current densities) with very low losses for relatively long times (several tens of microseconds), and the interruption of these currents in much shorter times (ultimately a few hundred nanoseconds). This paper reports the results of those experiments.

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Experiment

The experiments consisted of a parallel combination of an explosively driven current "breaker", a high speed fuse opening switch and a fixed inductance load coil separated by self-closing, low inductance surface tracking switches. Figure 2 shows the circuit employed in the experimental series. A relatively large, 1500 uF capacitor bank, charged to 20 KV, was employed as the primary current source. Energy from the bank was transferred to a storage inductor of 245 nH reaching a peak value of almost 1.2 MA in a time of about 32 microseconds. The timescale for the experiment was chosen because it is characteristic of the final, high energy gain, portion of the operation of a multimegajoule flux compression generator or of a relatively simple multi-megajoule capacitor bank.

During the charging time of the inductor, the current path was completed by current flowing in the explosively operated "breaker", OS1. Upon interruption, the "breaker" developed a relatively large voltage of about 18 kilovolts which was imposed across a low inductance surface tracking closing switch, CS1, causing the switch to close in multiple channels and connected the fuse in parallel with the now rising impedance of breaker. The initially low impedance of the fuse path diverts current from the
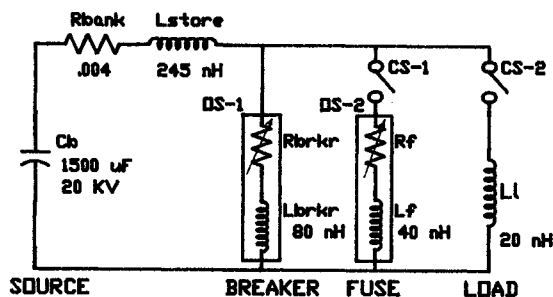

Figure 2 Staged Switching Circuit

breaker path allowing the breaker to "recover" electrical strength and increase in impedance. As the current flows in the fuse, however, the fuse begins to heat, and melt, as in conventional fuse operation. After a few microseconds the fuse vaporizes which results in a large increase in the impedance of the fuse path. The rising impedance impresses a large voltage across the now "recovered" breaker and across closing switch, CS2, which has, up to this point, isolated the power conditioning system from the inductive load. CS2 is also a surface tracking switch whose parameters are selected so that it closes at much higher voltage than did CS1. The much higher voltage developed by operation of the fuse compared to the initial charge voltage of the capacitor bank gives rise to a much larger dI/dt in the load inductor and greater power delivered to the load.

Explosive Actuated Breaker

For these experiments the breaker, which is an extension if a design suggested by NRL (5), consisted of a copper conductor .010" thick and 15 cm wide. The conductor was folded into a series of hairpin sections as shown in Figure 3 and was supported, and confined by insulating polyethylene blocks. The "hairpin" bend of the conductor surrounds a small (approx 7mm diameter) explosive charge which may consist of commercial detonator cord containing up to 300
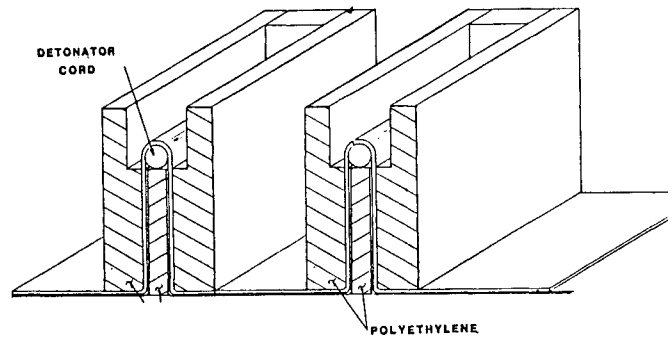

Figure 3 Explosive/Ruptured Conductor Switch

grains/ft PETN charge; but which for this experiment was a cylindrically extruded form of commercial "Deta-sheet" explosive consisting of about 80% PETN by weight in a flexible binder. The explosive charge is detonated in the center of the folded conductor and burns toward both outside edges at a speed of about 7 mm/uSec in each direction and rupturing the conductor in the process. The burn reaches the outer edge of the conductor about 10 uSec after detonation. As the burn approaches the edge of the strip the effective cross section of conductor presented to the current is reduced and the remaining conductor begins to heat rapidly -- and eventually the conductor melts, and vaporizes. Thus the final interrupting action of the breaker is a combination of a mechanical rupturing action and a fusing action in the rapidly reducing cross-section of the switch.

Fuse Opening Switch

The fuse opening switch used in position OS2 is representative of the high current, high speed fuse technology which has been developed at the AF Weapons Laboratory during the last 5 years. For this experimental sequence, the fuse was aluminum foil material .001" thick, shaped into two parallel strips each about 10 cm wide and 50 cm long. The fuse was configured in a low inductance, flat, package with a wide, rigid conductor returning current under the fuse. The foil material was surrounded by a "quench" material of commercial bead blasting material composed of soda-lime glass spheres with a uniform diameter of about 100 microns. The quench material serves to cool and condense the metal vapor from the exploded fuse and prevents the vapor from heating to the point where significant thermal ionization may lead to reconduction in the fuse.

Diagnostics

The breaker and the fuse are located on two adjacent arms of a cross shaped transmission line with the storage inductor and cable transmission lines to the capacitor bank occupying the third arm and the "theta-coil" inductive load occuping the fourth arm.
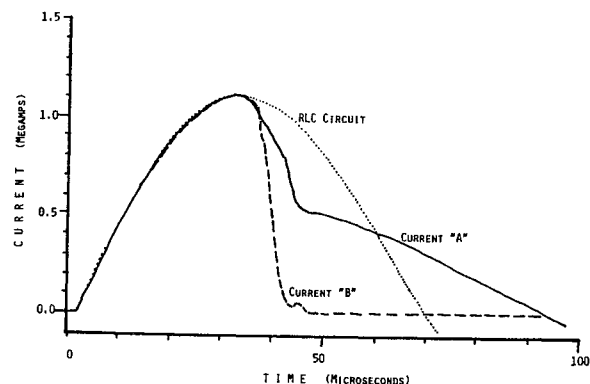

Figure 4   Line and Breaker Currents

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The connection between the central line and the breaker is hard bolted along the central axis of the transmission line and the closing switches CS1 and CS2 comprise the connecions on the transverse arms. Current measurments with Rogowski coil are made around each of the four arms of the line, and voltage measurements are made on the center of the line, on the fuse, and on the load sides of CS1 and CS2.

Results

The experimental configuration was chosen to maximize ease of operation and measurement and hence no effort was made to achieve maximum circuit efficiencies in either the overall system or the individual components. Figure 4 shows current recorded at the storage inductor ("A") and the current
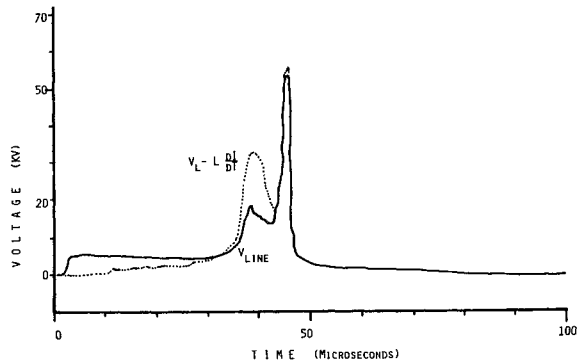
Figure 5   *Line Voltage (corrected)*

observed through the breaker branch of the circuit ("B"). Currents A and B are seen to rise together to a peak of about 1.2 MA in 31 microseconds. For comparison the analytic solution for the RLC circuit equivelant to the loop which charges the storage inductor is also plotted showing that the system current is virtually the "short circuit" current until
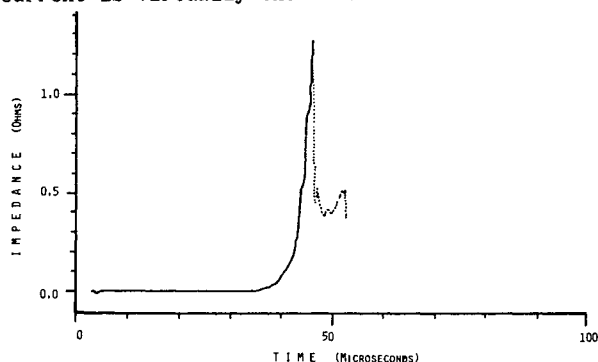
Figure 6   *Breaker Impedance (to peak)*

the impedance of the breaker begins to rise significantly at 33 microseconds after the beginning of the current. After the breaker begins to interrupt, the breaker current is seen to decrease very rapidly in 5-6 microseconds.

During the rise of current in the storage inductor, the voltage across the transmission line, shown in Figure 5, remains relatively constant at about 4.3 KV. The voltage across the resistive component of the breaker impedance is also plotted in Figure 5. This component is found by subtracting the contribution due to the 80 nH inductance of the breaker from the measured "line" voltage. It is seen to remain very low until the rupture of the breaker is begun by detonation of the HE at about 24 microseconds. The resistance of the breaker, computed from the ratio of the resistive component of the breaker voltage to the current ("B") in the breaker branch, is shown in Figure 6. Figure 7 shows the same
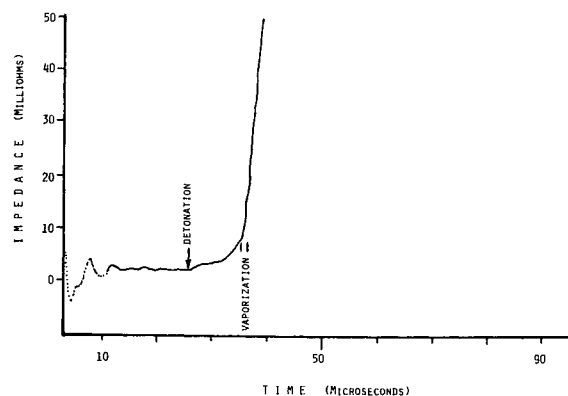
Figure 7   *Breaker Impedence (early expanded)*

resistance data on an expanded resistance scale to show the early time behavior of the breaker. From the initial rise of the current to the initiation of the small HE charge in the center of the breaker at 24 microseconds, the breaker resistance is virtually constant at 2.3 milliohms. This, somewhat tricky, measurement compares very favorably with the 2.0 milliohms that is expected for the 4 meter long strip of .010" copper foil which comprises the breaker. After the initiation of the charge, the resistance is seen to increase, first slowly, then more rapidly as the outward burning HE charge disrupts the conductor, reducing the current carrying cross-section. At 34 microseconds the 7mm/uSec burn of the HE has ruptured 7 of the 7.5 cm half-width of the conductor, leaving a conductor cross-section of 1 cm X .010" to carry fully 1 MA of current. Simple "action integral" calculations shows that under these conditions the copper conductor will reach burst specific action in less than 1 microsecond. Thus from 34 to 35 microseconds, the remaining conductor is rapidly vaporized while still being disrupted by the HE burn, and Figure 7 shows the rapid increase in breaker resistance accompaning this process. The total disrupted length of the breaker is about 8 cm and noting that resistivities of about 500 micro-ohm cm are common in electrically exploded conductors (6), the 1 cm wide section would be expected to display a resistance of about 0.4 ohms. As discussed below, the second (larger) voltage peak in Figure 5 is the result of the fast interruption of current by the second stage (fuse) switch, and a time correlated (but very small) peak is observed in current "B" in Figure 4. Figure 6 shows that the peak resistance of almost 1.3 ohms is observed to occur simultaneously with this second peak. The subsequent drop in resistance to about 0.5 ohms may be a real observation of the beginning breakdown or "restrike" in the breaker, but is more likely an inaccuracy in the measurements caused by the need to take the ratio between voltage and current when both have been reduced to very small
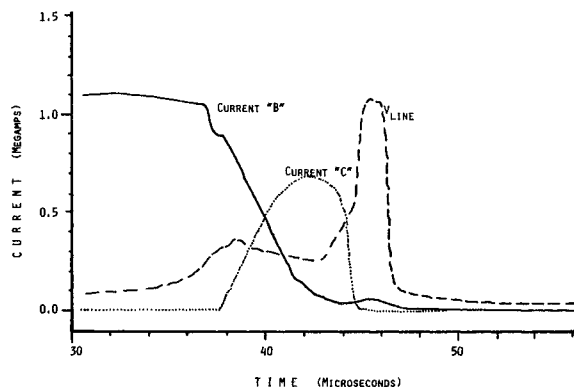
Figure 8   *Breaker and Fuse Currents*

values by the operation of the circuit. In either case, the 1.3 ohm resistance observed in Figure 6 is an indication of the significant improvement resulting from the HE disruption of the breaker conductor.

Figure 8 shows, on an expanded time scale, the breaker current "B" during the interruption, the current, "C", rising in the fuse branch, and the (normalized) voltage across the transmission line during the time when current is transferring from the breaker branch to the fuse branch. At about 37.7 microseconds the surface tracking switch closes, as shown by the onset of current in the fuse "C" (and by abrupt changes in current "B" and in the voltage). Voltage measurements made across the surface tracking switch result in approximate measure of the closing switch impedance and rough approximations of the (time changing) inductance of the switch which range from 35 - 75 nH. At this time about 900 KA is flowing in the storage inductor as measured by both current "A" and "B", and flux conservation applied to the two loop transfer process predicts currents from 600 to 700 KA in the combined inductance of fuse and closing switch depending upon the value chosen for switch inductance. Thus the measured value of peak fuse current of 680-690 KA observed in Figure 8 falls well within the range predicted by simple time independent circuit modeling. The fuse size was chosen to carry current for 6-7 microseconds before vaporization in order to allow time for the virtually complete transfer of current out of the breaker branch. Figure 9 shows the impedance of the fuse found from the ratio of the
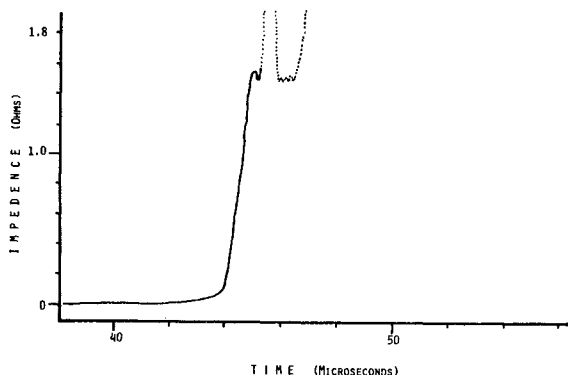
Figure 9   Fuse Impedance

resistive fuse voltage to the current in the fuse branch. Based on the 50 cm X 20 cm dimensions of the .001" aluminum fuse, the initial resistance is expected to be about 3 milliohms which compares very favorably with the measured data. Assuming the same 500 microohm-cm resistivity common to fast fuse vapor, the final resistance would be expected to be about 0.5 ohm. The somewhat larger values observed in Figure 13 where the resistance is seen to rise to about 1.5 ohms before the measurement loses significance can be attributed to the rapid transfer of current into the approximately 20 nH fixed inductive load.

Figure 10 shows the current ("D") transferred to the fixed load displayed on an expanded time scale. At 42 microseconds after current rise, when current begins to rise in the load, the current in the storage inductor is (from Figure 4) about 644 KA. Applying the same range of closing switch inductances observed in the breaker loop, flux conservation predicts currents between 450-500 KA in the load loop. And this again corresponds well to the 470 KA observed in Figure 10. Most significant, however, is the rise-time of the current in the load which is seen to be less than 500 nS. Thus the overall time compression of the system from the slow charge current to the current rise in the load is seen to be a factor of more than 70.
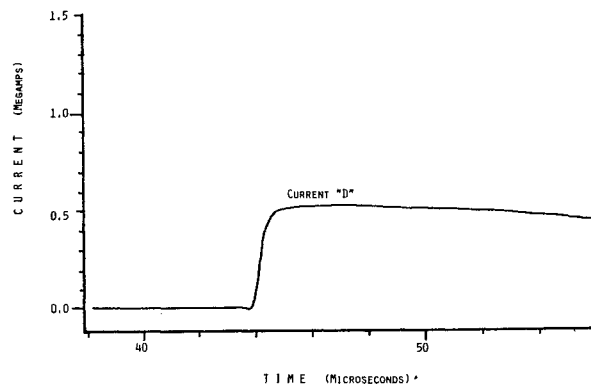
Figure 10   Load Current

Conclusion

This relatively simple experimental sequence demonstrated the viability of using a staged configuration of breakers and fuses to accomplish pulse compression from tens to tenths of microseconds with current efficiencies that fall well within those predicted by simple circuit considerations. The arrangement of the breaker and fuse employed in these experiments do not represent an optimized configuration for a compact, low cost system, but arriving at a suitable configuration is judged to be straight forward. Another important result of the experiment, is the extremely successful performance of the breaker which produced about 30 KV upon current interruption but which readily withstood more that 100 KV after about 5 microseconds of commutation time or at least a factor of 5 increase in holdoff strength. The obvious extension of this approach is a that of an integral breaker/fuse unit in which the "variable cross-section" nature of the breaker's operation is optimized to accomplish both switching operations in one package.

The experiment clearly demonstrated that the staged combination of breakers and fuses can be an effective method for compressing the output pulse of slow, high current systems such as flux compression generators and large slow capacitor banks in a way far more effective than direct application of fuses alone.

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